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Energy performance gap in refurbished German dwellings: Lesson learned from a field test

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ABSTRACT

Low insulation standards and obsolete heating systems of a large amount of buildings in Europe account for disproportional energy consumption. Within this project, the holistic renovation and the results from the monitoring activity of buildings from a field test, located in Southern Germany, are presented. The buildings, built at the end of the 1950s, have been retrofitted with seven different refurbishment layouts. The layouts differ in insulation and engineering system. An installed monitoring system collects thermal indoor environmental conditions and air quality conditions in rooms, as well as data about energy flows at delivery, distribution, storage and generation level, at high time resolution. The monitoring system allows a comparison between the real and the expected energy consumption of the buildings. The energy performance gap was identified and quantified for each refurbishment solution (with values up to 287% based on calculated savings): on average, the energy performance gap of the entire field test varied from 117% in 2011, 107% in 2012, 41% in 2013 and 60% in 2014. The occupants' behavior has been identified as one of the causes for the energy performance gap. Further causes are mistakes in the installation, and malfunctioning of the engineering system. The importance of a monitoring system for buildings with a complex engineering system was confirmed.

1. Introduction

The real energy consumption of buildings often differs significantly from the expected, calculated consumption, even if this is obtained using advanced, complex dynamic building energy performance simulation software. This phenomenon is well known and has been recently identified as the "Energy Performance Gap" [1] (EPG). In addition, the tendency of users of determinate products, to increase needs and elevate expectations when technology improvements are reached, is called "Rebound Effect".

The term "Rebound Effect", also known in the literature as the "Jevons Paradox", was coined by William Stanley Jevons and used in his book "The Coal Question: An Enquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal-mines" [2] already in the middle of the nineteenth century. In his book, Jevons asserts: "It is wholly a confusion of ideas to suppose that the economic use of fuel is equivalent to a diminished consumption. The very contrary is the truth".

A detailed discussion about the rebound effect and its impact on society, as well as a literature review of the rebound effect since Jevons definition, can be found in Polimeni et al. [3]. In general, the rebound effect distinguishes between direct and indirect. The direct rebound effect implies that an energy service becomes more efficient and therefore cheaper for a user, hence this service will be in higher demand than before. The indirect rebound effect implies that a user saves money for a certain energy service that became cheaper thanks to a technology development that makes this service more efficient. The user therefore utilizes the saved money for a new service that also requires energy. Within this work only the direct rebound effect is of interest.

A first use of the concept of the direct rebound effect for the building sector, as well as the introduction of the index "rebound share", was proposed by Haas et al. [4,5]. In their work, the authors defined (1):

$$Rebound\ Share = \frac{100\,(Calculated\ \ savings - Actual\ \ savings)}{Calculated\ \ savings}\% \quad (1)$$

The "calculated savings" of Eq. (1) express the amount of saved energy through a specific efficiency change in an existing building; however, in their works, the authors do not specify how this term should be calculated. There are two options to estimate this value, since this can be calculated as:

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- the difference between the calculated consumption before the retrofit and the calculated consumption after the retrofit,
- the difference between the measured consumption before the retrofit and the calculated consumption after the retrofit.

Furthermore, the use of the term "Rebound" is critical: in literature [1,3], the rebound is mainly connected to a change (direct or indirect [6]) of user behavior. But the definition in Eq. (1) does not distinguish whether the gap between expectations and observation is really caused by a change in behavior or by failures of the engineering system. This index could hence rather be called "energy saving deficit" (ESD), as proposed by Galvin [1], or "unachieved energy conservation share" as proposed by Haas and Biermayr [4] (see Section 3.3).

Evidence of the energy performance gap for new or retrofitted buildings is presented in the literature since the end of the 1990s, when Haas et al. [5] identified a gap between predicted (expected) and observed energy performances of buildings. The authors based their analysis on observations of about 400 retrofitted dwellings, and concluded that the rebound share, due to the retrofit, was between 15 and 30%. Two years later, Haas and Biermayr [4] calculated this index for approximately 500 dwellings, finding a rebound share between 20 and 30%. In both studies, the authors mainly concluded that "energy savings achieved in practice (and thus the reduction in CO_2 emissions) due to building retrofit measures will be lower than those calculated in engineering conservation studies".

Based on a field test data analysis of the German Energy Agency (DENA), Erhorn [7] showed a discrepancy of up to 300% between calculated and observed energy consumption for residential buildings.

More recently, Tronchin and Fabbri [8] tested three different computational methods to calculate the energy consumption of a single-family house located in Italy, and showed consistent differences between the predictions and the real consumption. They also pointed out that different calculation methods (static and dynamic) may lead to very different results.

Hens [9] illustrated the results of a "step-wise" retrofitting of the end of a row house located in Belgium, built in 1957 and monitored since 1978. For each retrofit action on the building (a.o. insulation, new windows, solar boiler) the author compared its calculated and its monitored energy performance and concluded that:

- the measured data show a net decrease of energy consumption by each improvement/retrofit,
- the decrease in energy consumption is consistently lower than predicted,
- wall insulation, new windows and better air tightness generate higher benefits than solar boiler and photo-voltaic panels.

Hens et al. [10] compared the observed and the calculated energy consumption of 964 dwellings finding a consistent discrepancy between expectations and observations.

In 2012 Sunnika-Blank and Galvin introduced the term "Prebound effect" [11] to evaluate the discrepancy between observed and calculated consumption of existing non-retrofitted buildings: they noted that the existing, not refurbished building stock, tends to consume less energy than expected (evaluating the buildings through calculation methods used for the energy pass certification procedures). They therefore advised scientists and policy makers that, when calculating the benefits of a retrofit of the existing building stock, the real consumption of non-retrofitted buildings should be used as a reference figure, instead of the calculated one. They argue that it is not possible to make energy savings, on energy that has not been consumed previously (before the retrofit).

Menezes et al. [12] analyzed the gap for a new office building, after what they called "a twelve month liability period" (they used the first year to optimize the building performance and reduce rough failures of the engineering system). They concluded that "There is significant evidence that buildings do not perform as well as predicted".

Dall'O et al. [13] compared the observed and expected (based on the calculation from energy pass certification procedures) consumption of 196 similar apartments in two residential "new high performance" buildings. They conclude that the consumption data are not homogeneous (due to occupants' behavior) and observed consumption may be higher than calculated.

Galvin [1] compared several studies on the rebound effect in the building sector concluding that there is no shared approach among scientists for evaluating building performances and discrepancies between observations and expectations. He also noted that in some of the analyzed literature, "rebound indexes" computed with different approaches were wrongly compared between each other. Further, the author introduced new indexes and new calculation methods to evaluate the discrepancies between observations and expectations and to compute the rebound effect.

deWilde [14] proposes a framework for investigation of the gap between predicted and measured performances of buildings and offers a relevant literature review on the topic. His pilot study showed that "the performance gap changes with external conditions (example given: outdoor temperature), and with the temporal resolution of the energy measure in use" (i.e. if the collected data are annual based or have a higher time resolution).

Further studies confirm the existence of a gap between expected and observed energy performances for cooling systems [15,16], heating systems and domestic hot water engineering systems [17–19].

In a nutshell, it can be concluded that previous studies confirm the presence of a gap between expected and observed energy performances of new and retrofitted buildings. This gap is caused by engineering systems that are not performing as expected, and by occupants' behavioral issues.

Within this work, the refurbishment of a field test with three demonstration buildings with 30 apartments each is described. The buildings have been retrofitted with different strategies and are monitored since 2011 in high time resolution.

The objectives of this work are:

1. Discuss existing indexes and define new indexes to evaluate the performances of both new and refurbished buildings;
2. Based on the collected data, verify the existence of the energy performance gap for the demonstration buildings and quantify this;
3. Evaluate the level of success of each retrofit layout (based on the analysis of the primary energy consumption of the buildings);
4. Evaluate the causes for the identified energy performance gap;
5. Analyze occupants' diversity in big apartment buildings.

The description of the buildings and of the monitored system is presented in Section 2. In Section 3 the methods for the evaluation of the buildings' retrofit are illustrated, and in Section 4 the results are explained and commented. Finally, the reasons for the gap between observations and expectations are analyzed and discussed.

2. Description of the demonstration buildings and monitoring system

Three demonstration buildings located in southern Germany have been selected for a field test. The buildings were built at the